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MEMORANDUM FOR PRS (In-House/Contractor Publication)

FROM: PROI (STINFO) 18 July 2002

SUBJECT: Authorization for Release of Technical Information, Control Number: **AFRL-PR-ED-VG-2002-184**
Doug Talley (PRSA) et al., "Supercritical and Transcritical Shear Flows in Microgravity: Experiments and Direct Numerical Simulations" (viewgraphs)

56174

6th Microgravity Fluid Physics & Transport Phenomena Conf. **(Statement A)**
(Cleveland, OH, 14-16 August 2002) (Deadline: 15 August 2002)

SUPERCRITICAL AND TRANSCRITICAL SHEAR FLOWS IN MICROGRAVITY: EXPERIMENTS AND DIRECT NUMERICAL SIMULATIONS

Doug Talley
Air Force Research Lab

Josette Bellan
Jet Propulsion Lab

Bruce Chehroudi
ERC, Inc.

Objectives

- Determine the fluid physics governing transport and mixing in non-reacting transcritical and supercritical mixing layers.

Overall approach

- Extend extensive previous experience in modeling and performing similar experiments in normal gravity to μg.

Projected outcome

- A validated fluid physics model.

Status

- Started April 2002.

Unconventional mixing layer features

- Large density gradients, like sprays, but with vanishing surface tension and enthalpy of vaporization.
- For mixtures, strongly enhanced solubility of the “gas” phase into the “liquid” phase.
- Reduced “gas” phase diffusivity (more liquid-like).
- Large property excursions near the critical point
  - Conductivity, viscosity, speed of sound, specific heats.
- Mixing induced critical point variations.
- Enhanced “gas” phase unsteadiness.
- “Real fluid” properties must be taken into account

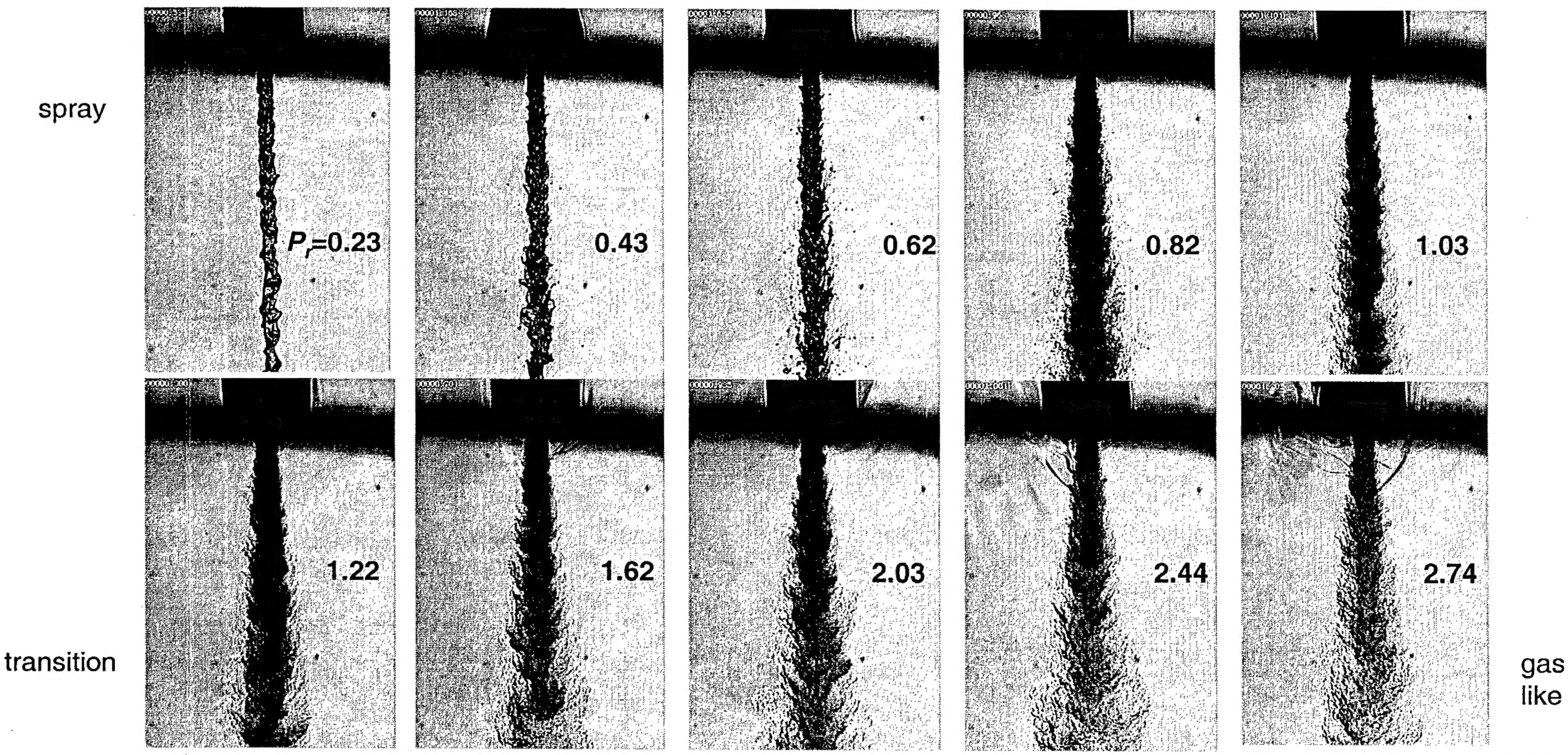
High pressure propulsion and mixing applications

High Reynolds number jets at 1g

LN2 injected into GN2

P_{cr} = 3.39 MPa **T_{amb} = 300 K** **Re = 25,000- 75,000**

T_{cr} = 126 K **T_{inj} = 99-120 K** **V_{inj} = 10-15 m/s**



Chehroudi, et. al., *Phys. Fluids*, vol. 14, no. 2, pp.850-861, 2002

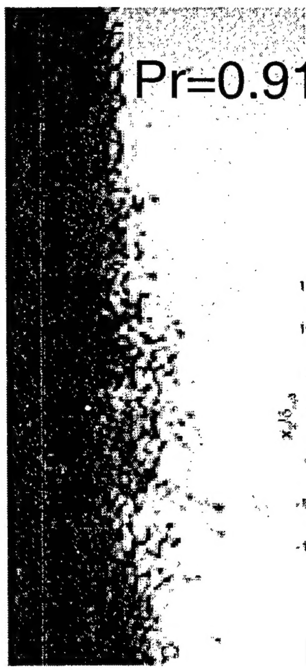
AFRL

Turbulent mixing layer structure at 1g

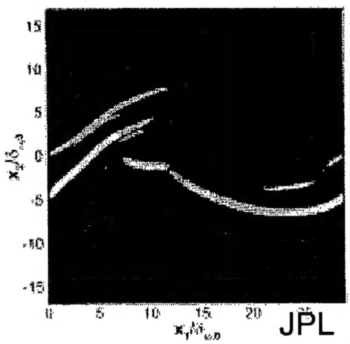
LN2 injected into GN2

P_{cr} = 3.39 MPa **T_{amb} = 300 K** **Re = 25,000- 75,000**

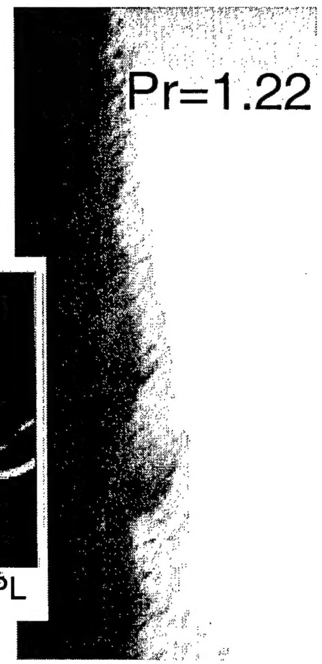
T_{cr} = 126 K **T_{inj} = 99-120 K** **V_{inj} = 10-15 m/s**



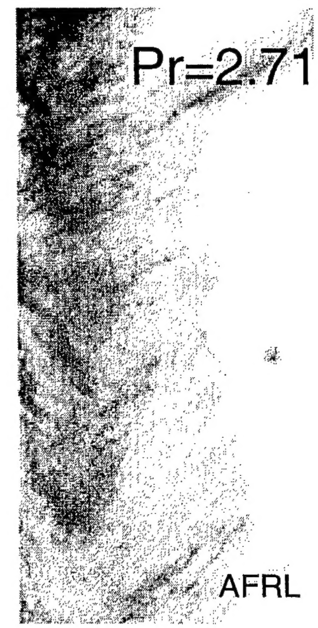
Low Pres.
Subcritical
Droplets



DNS may be capturing transitional structures (not yet validated)



Mod. Pres.
Supercritical
Transition



High Pres.
Supercritical
Gas layers

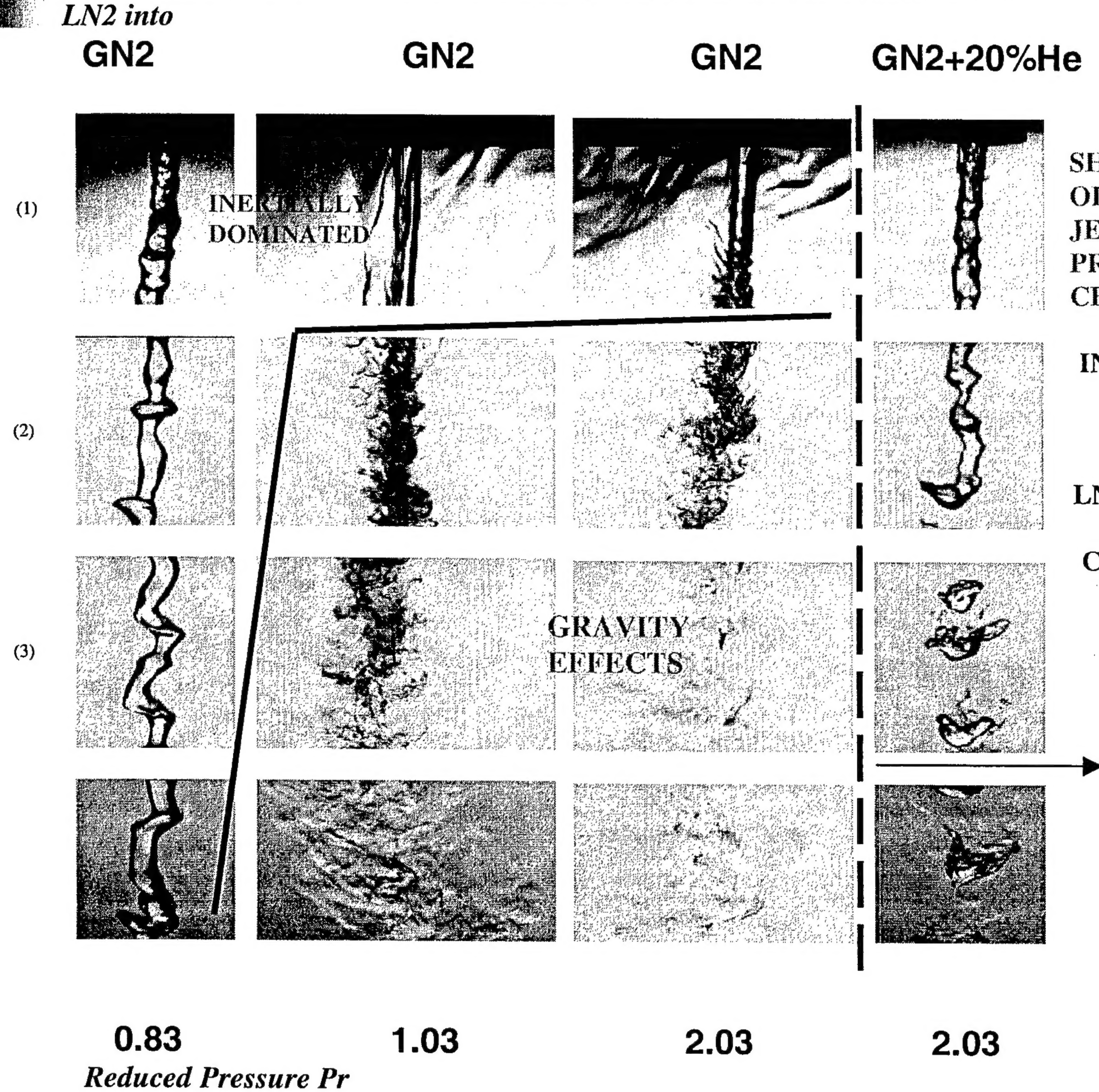
Chehroudi, et. al., *Phys. Fluids*, vol. 14, no. 2, pp.850-861, 2002; Miller, et.al., *J. Fluid Mech.*, 436, 1-39, 2001

The argument for μg

- To remain inertially dominated far enough downstream for adequate experimental resolution, the required velocities at 1g invariably cause turbulence
  - Introduces need for turbulence models
  - No validated supercritical / transcritical turbulence models currently exist
- Validation of a fluid physics model without the complications introduced by turbulence requires laminar flows

Microgravity is required to produce inertially dominated laminar flows far enough downstream for adequate experimental resolution

Low Reynolds number jets at 1g



SHADOWGRAPH IMAGES OF LIQUID NITROGEN JETS ISSUING INTO A PRESSURIZED CHAMBER.

INJ. DIAMETER: 0.25 mm

Re: 3350 - 4090

LN2 TEMPERATURE: 87K

CHAMBER TEMP. : 292K

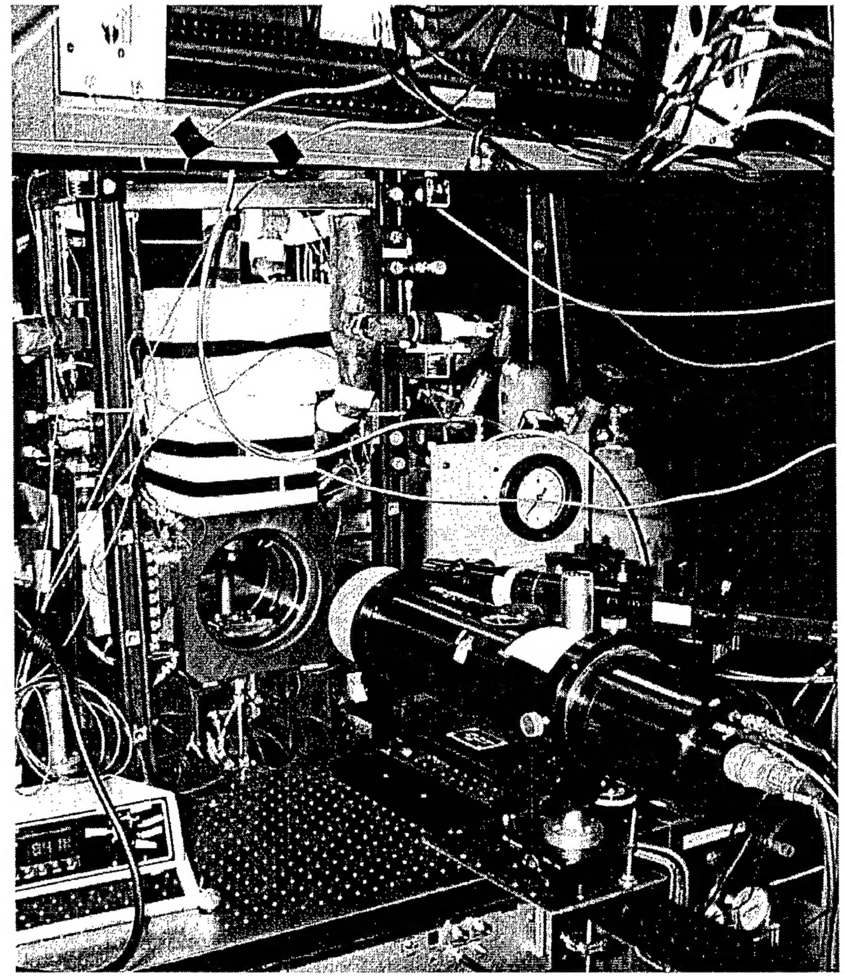
GRAVITY EFFECTS NOT CALCULATED

Mayer, et. al., *J. Propulsion and Power,* vol. 14, no. 5, pp.835-842, 1998

Experimental approach

Adapt successful 1g experiment to μg

- Windowed pressure vessel at supercritical pressures.
- Cryogenic LN2 / GN2 / GHe produces transcritical effects w/o need for heating
- Shadowgraph, Schlieren, visualization of flow fields.
  - Shapes and time evolution of structures
  - Core lengths, spreading rates, wavelengths



DNS approach

3D transient transport equations, with a Peng-Robinson EOS and cross-diffusion and non-equilibrium effects through fluctuation - dissipation theory

Model equations

$$\frac{\partial \rho}{\partial t} + \frac{\partial}{\partial x_j}[\rho u_j] = 0$$

$$\frac{\partial}{\partial t}(\rho u_i) + \frac{\partial}{\partial x_j}[\rho u_i u_j + p\delta_{ij} - \tau_{ij}] = 0$$

$$\frac{\partial}{\partial t}(\rho e_t) + \frac{\partial}{\partial x_j}[(\rho e_t + p)u_j - u_i\tau_{ij} + q_{j,IK}] = 0$$

$$\frac{\partial}{\partial t}(\rho Y_2) + \frac{\partial}{\partial x_j}[\rho Y_2 u_j + j_{2j}] = 0$$

where the fluxes are calculated according to fluctuation – dissipation theory

$$q_{j,IK} = -\left[\lambda'_{ik}\frac{\partial T}{\partial x_j} + \alpha_{IK} R_u T\left(\frac{m}{m_2 m_1}\right) j'_{2j}\right]$$

$$j_{2j} = -\left[j'_j + \frac{\alpha_{BK} Y_2 Y_1 \rho D}{T}\frac{\partial T}{\partial x_j}\right]$$

$$j'_{2j} = \rho D\left[\alpha_D \frac{\partial Y_2}{\partial x_j} + \frac{Y_2 Y_1}{R_u T}\left(\frac{m_2 m_1}{m}\right)\left(\frac{v_{,2}}{m_2} - \frac{v_{,1}}{m_1}\right)\frac{\partial p}{\partial x_j}\right]$$

Peng – Robinson equation of state

$$p = R_u T/(v - B_m) - A_m/(v^2 + 2vB_m - B_m^2)$$

where

$$A_m = \sum_\alpha \sum_\beta X_\alpha X_\beta A_{\alpha\beta} \qquad B_m = \sum_\alpha X_\alpha B_\alpha$$

From this EOS one may calculate

$$v_{,\alpha} = \partial v/\partial X_\alpha \qquad h_{,\alpha} = \partial h/\partial X_\alpha$$

and

$$\alpha_D = 1 + X_\alpha \frac{\partial \ln(\varphi_\alpha)}{\partial X_\alpha}$$

where

$$v = X_1 v_{,1} + X_2 v_{,2} \qquad h = X_1 h_{,1} + X_2 h_{,2}$$

Mixture transport properties

Thermal conductivity

$$\lambda'_{IK} = \lambda + X_1 X_2 \alpha_{BK} \alpha_{IK} R_u \rho D / m, \ \lim_{p\to 0} \lambda = \lambda_{KT}$$

Thermal diffusion factor

$$\alpha_{IK} = \alpha_{BK} + \frac{1}{R_u T}\left(\frac{m_2 m_1}{m}\right)\left(\frac{h_{,2}}{m_2} - \frac{h_{,1}}{m_1}\right), \ \lim_{p\to 0} \alpha_{BK} = \alpha_{KT}$$

Viscosity

$$\mu = \mu_R \left(\frac{T}{(T_1 + T_2)/2}\right)^{0.7}$$ *T* in Kelvins

Diffusivity: considerations on the range of scales that can be resolved indicates a limited thermodynamic state space

$$600K \le T \le 1100K, \quad 40atm \le p \le 80atm$$

wherein qualitatively correct trends are given by

$$Sc = \frac{\mu}{\rho \alpha_D D} = 1.5 - Y_2, \quad \Pr = \frac{\mu C_p / m}{\lambda} = \frac{Sc}{2\exp(-3Y_2/2)}$$

Work Plan

- Year 1
  - Design and fab experiment; begin 1g checkouts
  - Begin DNS of temporal N2/N2 mixing layers
- Year 2
  - Begin μg experiments in N2/N2 mixing layers
  - Begin DNS of spatial N2/N2 mixing layers
- Year 3
  - Complete μg experiments in N2/N2 mixing layers
  - Perform DNS of μg experiments
- Year 4
  - Perform initial μg experiments of N2/He mixing layers
  - Final report
- N2/He work will be extended as time permits